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ARTICLE

Provenance of the Devonian–Carboniferous clastics of the southern part of the Prikolyma terrane (Verkhoyansk–Kolyma orogen) based on U–Pb dating of detrital zircons

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ABSTRACT

U–Pb dating of detrital zircons collected from the Middle–Upper Palaeozoic strata of the Prikolyma terrane (Verkhoyansk–Kolyma orogen) provide the first insight into provenance areas and the Middle–Late Palaeozoic geological history of the Russian Far East. Detrital zircon ages from the Lower–Middle Devonian sandstones group around 395–405 M (Emsian–Eifelian) which correlate well to trachyte of the Uvyazka zone and the Kedon Complex of the North Okhotsk active continental margin located on the Omolon terrane. Precambrian-aged zircons group around 1740–2080 and 2460–2800 Ma, respectively, suggesting possible sources within metamorphic rocks of the basement of the Omolon terrane or the Siberian Craton. The majority of the zircons from the Lower and Upper Carboniferous sandstones group around 333–375 Ma, suggesting that the principle source of the clastics were volcanic rocks and comagmatic felsic intrusions of the Kedon Complex of the North Okhotsk active continental margin. Our new data allow us to evaluate and revise the available palaeotectonic reconstructions of northeast Asia for the Devonian and Carboniferous.

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Northeast Asia; Verkhoyansk–Kolyma orogen; Prikolyma terrane; Devonian–Carboniferous paleogeography; detrital zircon

Introduction

The bedrock of the Russian Far East is comprised of a complex network of accretionary terranes, representing a long period of crustal growth since the Late Palaeozoic. The main orogenic belt, the Verkhoyansk–Kolyma orogen, formed as a result of collision of the Kolyma–Omolon superterrane (microcontinent) with Siberia in the Late Mesozoic (e.g., Şengör & Natal'in 1996; Parfenov & Kuzmin 2001; Parfenov et al. 2003; Nokleberg 2010). Although the Late Mesozoic geological history of the composite Kolyma–Omolon superterrane is relatively well understood, the superterrane comprises a collage of fault-bounded blocks (terranes), amalgamated in Jurassic time, whose origins and geological history throughout the Palaeozoic and Early Mesozoic remain somewhat enigmatic.

The Prikolyma terrane (PT) forms the southeastern part of the composite Kolyma–Omolon microcontinent (eastern part of the Verkhoyansk–Kolyma orogen), extending over 475 km in length and 125 km in width. The PT is composed of intensely deformed rocks variable in age from Palaeoproterozoic to Carboniferous, with an estimated thickness of over 10 km, overlain by less deformed Permian and Mesozoic clastic and volcanoclastic rocks (e.g., Grinberg et al. 1981; Tretyakov 1987; Parfenov & Kuzmin 2001; Nokleberg et al. 2001). The PT is bordered to the east by the Omolon and Sugoi terranes, and to the south by the Omulevka terrane (Fig. 1). Its northern and western boundaries are overlain by Mesozoic and Cenozoic rocks of the Indigirka–Zyryanka sedimentary basin and Quaternary deposits of the Kolyma River. According to modern palaeotectonic reconstructions, the PT formed part of the Siberian Craton in the Early–Middle Palaeozoic, before rifting during the Devonian which ultimately resulted in opening of the Oimyakon ocean basin. After closure of the Oimyakon ocean in the Late Mesozoic, it is supposed that the PT, as a constituent part of the Kolyma–Omolon microcontinent, collided with the eastern margin of the Siberian Craton and became incorporated into the Verkhoyansk–Kolyma orogen (e.g., Şengör & Natal'in 1996; Parfenov & Kuzmin 2001; Parfenov et al. 2003; Nokleberg 2010).

Detrital zircon provenance studies are an effective approach for reconstructing links between sedimentary basins and their clastic source regions, providing an independent test of the affinity of rocks in provenance regions. A long history of tectonic processes such as rifting and continental accretion can often shift discrete continental terranes far from where they originally formed. Therefore, detrital zircon provenance studies represent a powerful tool for elucidating their affinity and geological evolution. Here, we present the first detrital zircon study of Middle–Upper Palaeozoic strata of the PT.

Our primary objectives were: (1) U–Pb dating of detrital zircons from the Middle–Upper Palaeozoic clastics of the PT; and (2) to use the detrital zircon data to evaluate the palaeotectonic reconstructions proposed by Şengör & Natal'in

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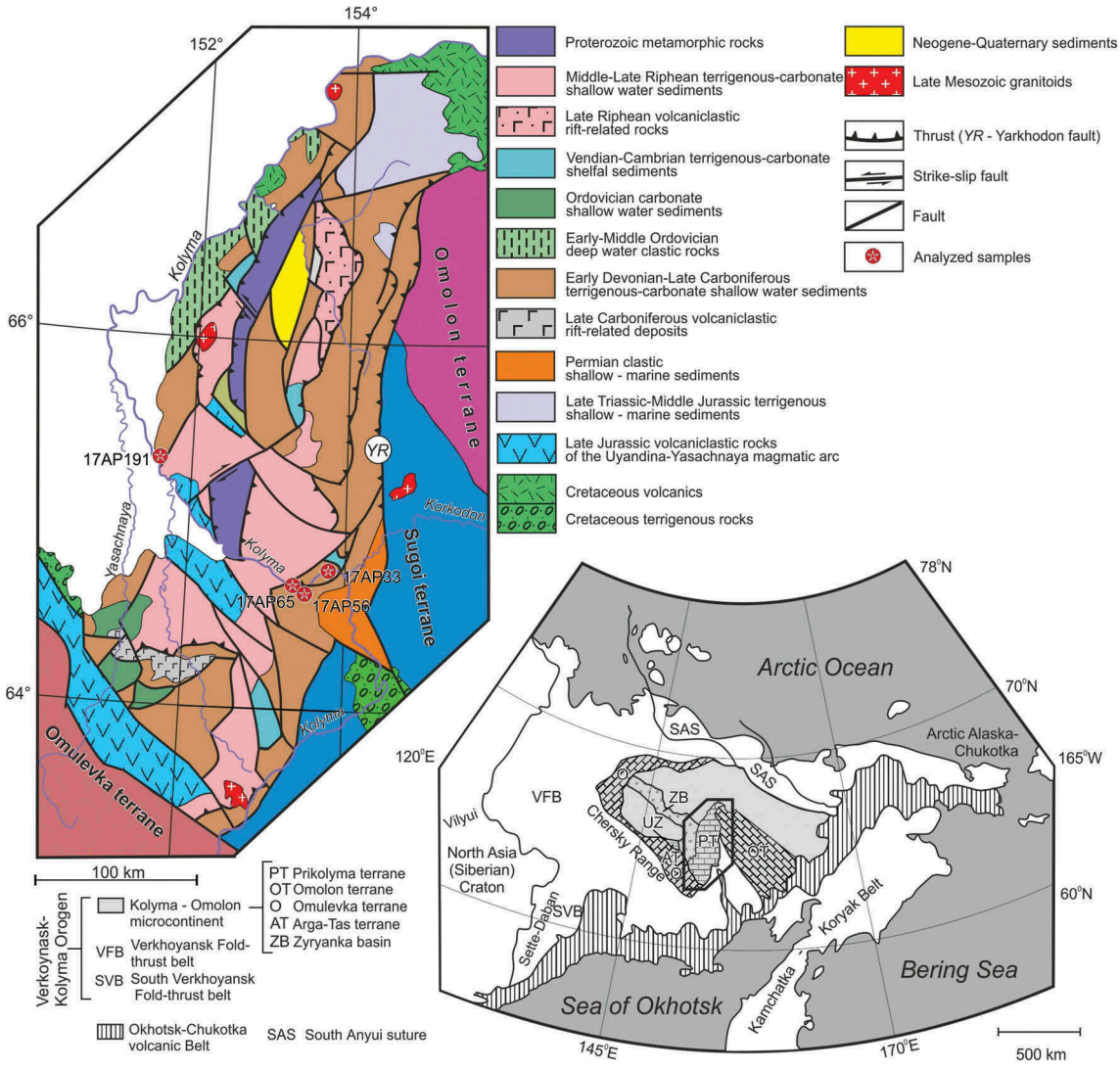

Figure 1. Main geological units of the Prikolyma terrane (modified Parfenov & Kuzmin 2001; Tretyakov 2016). Inset map shows location of the region and main tectonic units.

(1996), Parfenov & Kuzmin (2001), Parfenov et al. (2003) and Nokleberg (2010).

The results presented here provide new constraints on the Palaeozoic tectonics and paleogeography of the Russian Far East.

Geological setting of the southern part of the Prikolyma terrane

The oldest rocks of the terrane include Palaeoproterozoic schists exposed in its axial zone. In the south, the Riphean strata are composed of terrigenous-carbonate and volcanoclastic rocks (up to 5000 m in thickness). The Vendian rocks (1200–1400 m) rest on different stratigraphic levels of the Riphean with an angular unconformity at the base and consist of sandstones, siltstones, dolomites, and conglomerates, conformably overlain by a similar succession of Lower Cambrian rocks (25–300 m). The Lower Ordovician rocks (up to 2000 m) are exposed on the south-western flank of the PT and comprise a thick carbonate unit with sandstones and conglomerates at the base. The Devonian rocks in the south of the terrane include limestones, dolomites, calcareous sandstones, marls, and tuffs (1000–1400 m). They are overlain by a Carboniferous–Permian rock unit comprising tuffs, limestones and clastics (up to 1000 m) (Parfenov & Kuzmin 2001). Triassic–Middle Jurassic clastics (600–1000 m) crop out in the south-east of the terrane, unconformably overlain by Upper Jurassic volcanic rocks of the Uyandina–Yasachnaya magmatic arc (500–700 m) and Lower Cretaceous volcanoclastic rocks (up to 1000 m) of the Omsukchan basin of the Okhotsk–Chukotka volcano-plutonic belt (Fig. 2). Precambrian, Palaeozoic, Triassic and Jurassic rocks are intensely deformed (Tretyakov 1987, 2016).

LA-ICP-MS zircon U–Pb analysis

Samples were analyzed for detrital zircon U–Pb ages at the UTChron geochronology facility in the Department of Geological Sciences at the University of Texas, Austin. Samples underwent conventional heavy mineral separation and were grain mounted (no polishing) on one inch round epoxy pucks with double sided tape. All grains were depth-profiled using a Photon Machines Analyte

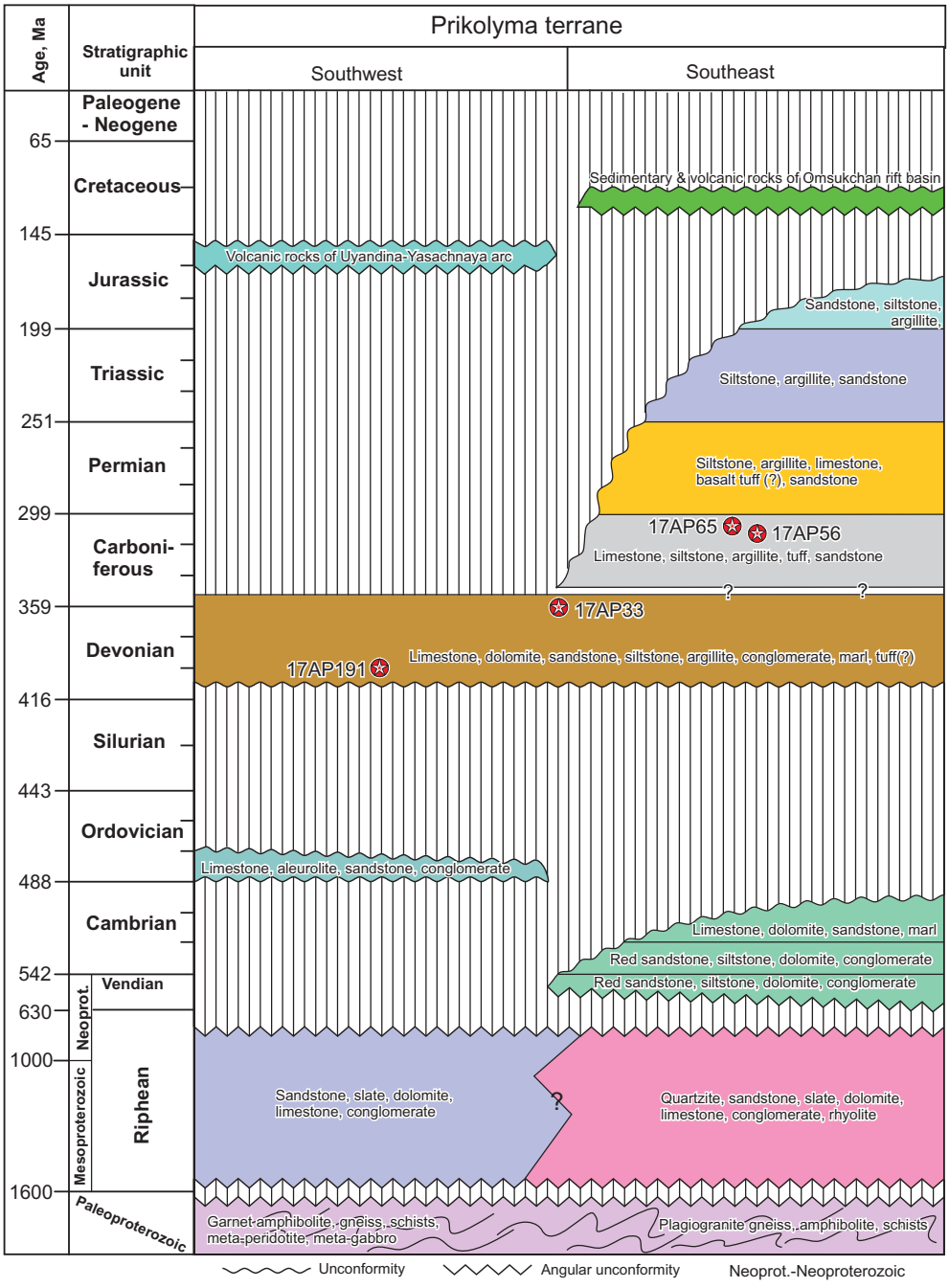

Figure 2. Generalized stratigraphic column of the southern part of the Prikolyma terrane and sample locations.

G2 ATLex 300si ArF 193 nm Excimer Laser, equipped with a Helix two-volume ablation cell. The ablated aerosols were transported using He gas to, and analyzed with, a Thermo Fisher Element2 single collector, magnetic sector-ICP-MS. $^{206}Pb/^{238}U$ ages are reported for ages younger than 1000 Ma. A description of the analytical approach as well as all detrital zircon U–Pb analytical results are provided in the Supplementary data.

Results and interpretation

Four samples of clastic rocks were collected from the Devonian and Carboniferous strata (stratigraphy based on Shishkin 1986) during field work carried out along the Kolyma River in the southern PT in 2017 (Figs. 1 and 2, Table 1).

Sample 17AP191 was collected from the Emsian–Eifelian Sakhin Formation and sample 17AP33 from the Upper Devonian–Lower Carboniferous Duksunda Formation (see Figs. 1 and 2). Precambrian detrital zircon age spectra from these rocks show a close similarity (Fig. 3). A significant number of detrital zircons yielded Palaeoproterozoic and Neoarchean ages, with distinct peaks in the age range 1740–2080 and 2460–2800 Ma, respectively. The oldest grain has an age of c. 3500 Ma. A possible source for Palaeoproterozoic and Archean zircons are metamorphic complexes of the basement of the Omolon terrane, located to the east of the PT (Akinin & Zhulanova 2016; Shevchenko et al.

Table 1. Summary of lithologies and locations of analyzed samples.

Sample number	Latitude, Longitude	Lithology	Stratigraphic age*; Formation
17AP33	N64°45′06.2′′, E153°48′11.7′′	Sandy metashale. The rock consists of 70–80% of fine-grained quartz with rare small-size grains of plagioclase. Sericite and muscovite are developed along the cleavage planes.	Upper Devonian–Lower Carboniferous; Duksunda Formation
17AP56	N64°38′56.0′′, E153°32′29.7′′	Fine-grained quartz-rich metasandstone with carbonate matrix.	Upper Carboniferous; Lyagayak Formation
17AP65	N64°38′26.8′′, E153°30′02.2′′	Fine-grained metasandstone. The rock is composed of small grains of quartz, carbonate, and plagioclase in approximately equal quantities.	Upper Carboniferous; Lyagayak Formation
17AP191	N65°18′11.2′′, E151°33′30.3′′	Fine- to medium-grained arkosic arenite. Clastic grains are mainly quartz and feldspar in composition with subordinate lithic grains (mainly volcanic).	Lower–Middle Devonian (Emsian–Eifelian); Sakhin Formation

* Paleontological data on stratigraphic age of the studied samples are provided in Supplementary file 3.

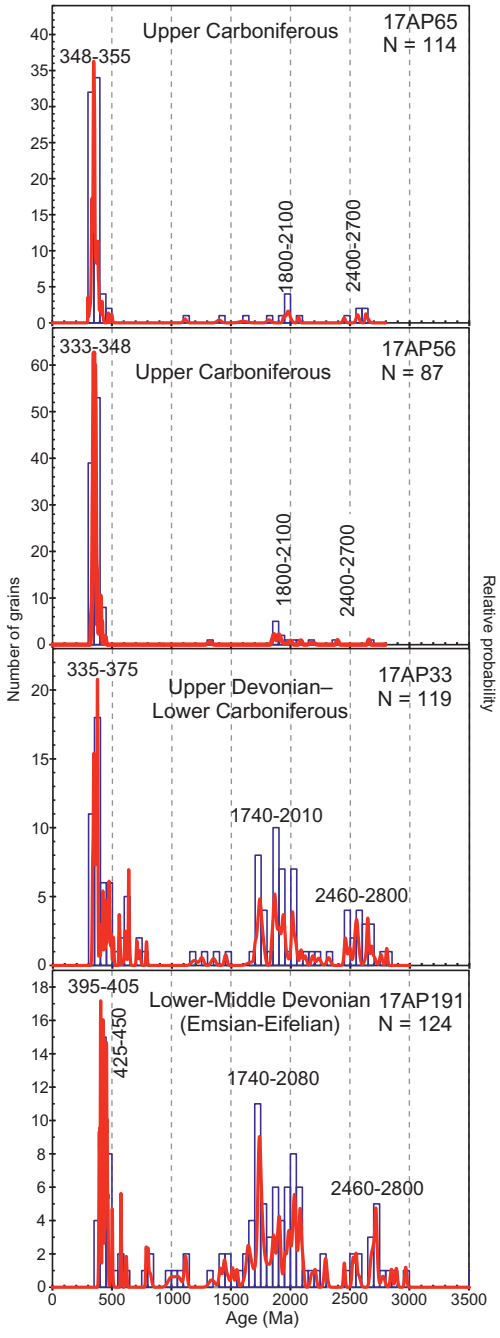

Figure 3. Probability density plot depicting the U–Pb detrital zircon data from Devonian–Carboniferous samples analyzed in this paper.

2000; Shevchenko 2006). The origin of the Neoproterozoic–Mesoproterozoic zircons (a few percent within dated grains) is unclear, due to the absence of magmatic and metamorphic rocks of this age across this part of the Verkhoyansk–Kolyma orogen. They could have been supplied by erosion and reworking of zircons from Riphean, Vendian, and Cambrian sedimentary rocks, but no detrital zircon ages are available yet from these rocks. The age spectra of the Palaeozoic zircon grains in the analyzed samples differ from each other (see Fig. 3). The youngest prominent peak from sample 17AP191 is at 395–405 Ma (late Early–early Middle Devonian). In northeast Asia, rocks of this age have been reliably constrained in the Uvyazka zone, at the boundary between the Omulevka and Arga-Tas terranes, c. 300 km to the northwest of the PT (395 ± 2.9 Ma, U–Pb on zircon grains, SHRIMP-RG at the Stanford-USGS, Prokopiev et al. 2007) and in the Omolon terrane (Kedon Complex of the North Okhotsk active continental margin, Gagieva & Zhulanova 2011).

The youngest zircons in sample 17AP33 form a peak at 335 Ma (25% of the dated grains) (see Fig. 3). Based on the age of the youngest grains, it can be assumed that the maximum depositional age of the rocks in this part of the Duksunda Formation is Early Carboniferous. The potential sources for these Carboniferous grains could be Devonian–Early Carboniferous subduction-related volcanic rocks of the Kedon Complex and comagmatic felsic intrusions (Gagieva & Zhulanova 2011; Glukhov et al. 2019; Goryachev et al. 2017) within the North Okhotsk active continental margin, which are widespread in the Omolon terrane. Alternatively, the studied rock series of the PT may themselves constitute part of the Kedon Complex.

Two dated samples originated from Carboniferous sandstones of the Lyagayak Formation (17AP56 and 17AP65) (see Figs. 1 and 2). Based on the ages of the youngest group of detrital zircons, the Lyagayak Formation has a Late Carboniferous maximum depositional age. 92% of zircon grains from these samples form age peaks at 333–348 and 348–355 Ma (see Fig. 3). The source of zircons of this age, as in sample 17AP33 described above, could be volcaniclastic rocks of the Kedon Complex and comagmatic felsic intrusions within the North Okhotsk active continental margin. Our data show that the main phase of island-arc magmatism within the North Okhotsk active continental margin occurred in the Early Carboniferous (Tournaisian–

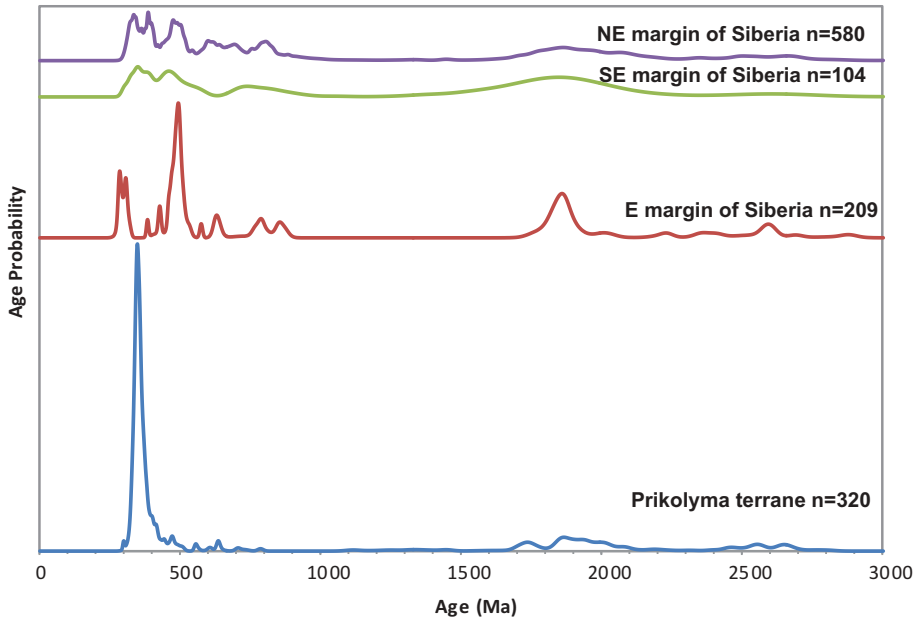

Figure 4. Comparison of detrital zircon age spectra of Carboniferous rocks from the Prikolyma terrane (this study), NE margin of Siberia (Ershova et al. 2013; 2015; Prokopiev et al. 2013), E and SE margin of Siberia (Prokopiev et al. 2008).

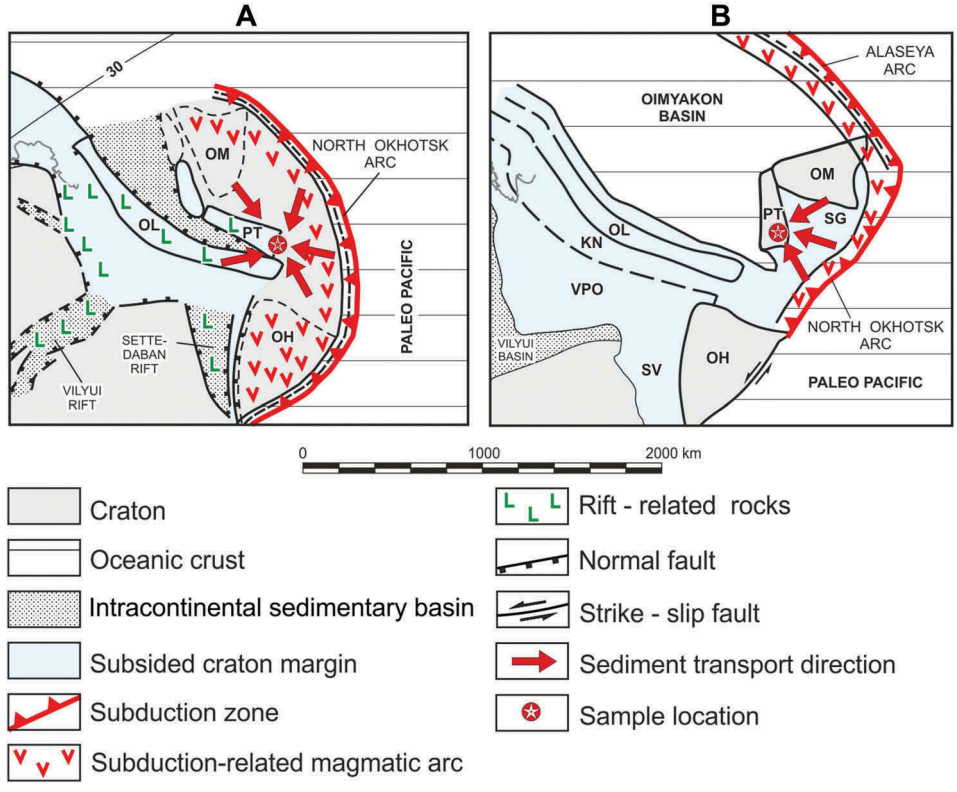

Figure 5. Palaeotectonic reconstructions for the Early Devonian (A) and Carboniferous (B) (modified from Şengör & Natal'in 1996; Parfenov & Kuzmin 2001; Parfenov et al. 2003; Nokleberg 2010). Terranes: PT – Prikolyma, OM – Omolon, OL – Omulevka, OH – Okhotsk, SG – Sugoi, KN – Kular-Nera. VPO – Verkhoyansk passive margin. SV – South Verkhoyansk.

Visean), rather than in the Late Devonian as previously supposed (e.g., Sosunov et al. 1982; Parfenov & Kuzmin 2001). Furthermore, the prevalence of Early Carboniferous zircon grains suggests the occurrence of volcanic processes immediately adjacent to the southern PT, coeval with sedimentation. Neoarchean and Palaeoproterozoic zircons are subordinate in the Lyagayak Formation and do not form prominent peaks, with possible sources from the basement

of the PT or Omolon terranes (e.g., Shevchenko et al. 2000; Shevchenko 2006).

Conclusion

U–Pb dating of detrital zircons from Devonian–Carboniferous sandstones in the southern part of the Prikolyma terrane (PT) showed: (1) The main provenances of clastic material for these strata are Devonian–Early Carboniferous volcaniclastic rocks of the North Okhotsk active continental margin, Precambrian complexes of the Omolon terrane, Early to Middle Devonian magmatic rocks of the southeastern flank of the Omulevka terrane and, likely, Late Precambrian sedimentary rocks of the PT. (2) We show that the subduction-related magmatism within the North Okhotsk active continental margin occurred in the Early Carboniferous (Tournaisian–Visean), and not exclusively in the Devonian as previously supposed (e.g., Gagieva & Zhulanova 2011; Sosunov et al. 1982; Parfenov & Kuzmin 2001). (3) The age spectra obtained from Carboniferous deposits of the PT are different to those from the north-eastern and eastern passive continental margins of Siberia (Fig. 4), confirming the existence of an oceanic basin (Oimyakon Basin) between the PT and Siberia by the Carboniferous. (4) Our data allow us to test and revise the available palaeotectonic reconstructions of northeast Asia for the Devonian and Carboniferous (Fig. 5). Based on the distribution of detrital zircons from the Lower–Middle Devonian strata of the PT, we can conclude that the PT formed a part of the eastern margin of Siberia at the end of the Early Devonian. Our new data support previously proposed models (Şengör & Natal'in 1996; Parfenov & Kuzmin 2001; Parfenov et al. 2003; Nokleberg 2010) claiming that Late Devonian–Early Carboniferous continental rifting in eastern Siberia (Vilyui and Sette-Daban) culminated in opening of the Oimyakon Ocean during the Middle–Late Palaeozoic, leading to significant geographic separation between the Prikolyma terrane and Siberia.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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